Charge-coupled Devices

Overview

Real world   Optics   Recorder   Digitizer   Vision and Graphics

Charge-coupled devices:

    MOS capacitors
    Charge transfer
    Architectures
    Color
    Limitations

Charge-coupled devices

The most popular image recording technology for 3D photography is the charge-coupled device (CCD).

- Image is readily digitized
- CCD cells respond linearly to irradiance
  - *But, camera makers often re-map the values to correct for TV monitor gamma or to behave like film*
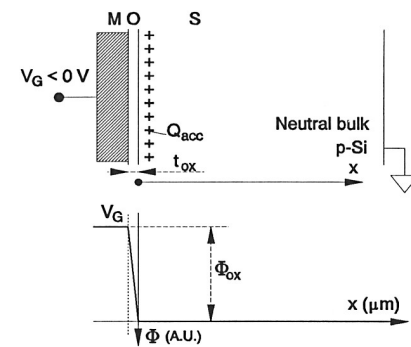- Available at low cost

Key elements:

- Photodetector
- Charge transfer mechanism

A MOS capacitor can do both of these…
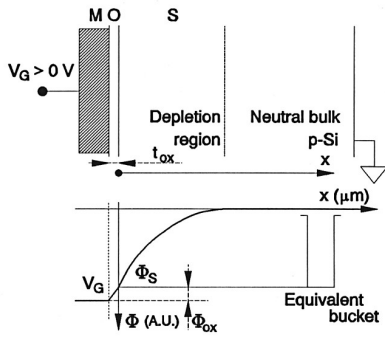

MOS capacitor

Negative gate voltage:

Majority carriers (holes) plentiful, and the gate behaves like a capacitor that stores positive charge near the oxide.

MOS capacitor in deep depletion
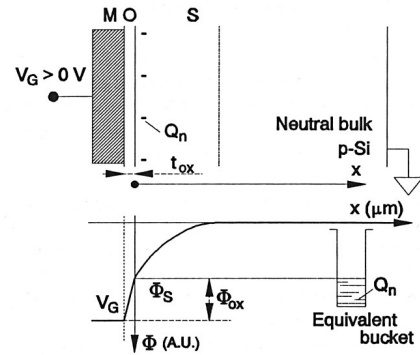

Positive gate voltage:

No minority carriers (electrons) to balance the voltage.

Holes are repelled, leaving negative charged ions in the depletion region.

Voltage drop in the silicon is like an empty bucket waiting to be filled by electrons. Bucket depth is proportional to applied voltage.

MOS capacitor in weak inversion

Positive gate voltage + new electrons:

Electrons are made available through a process such as photoelectric generation of hole-electron pairs.
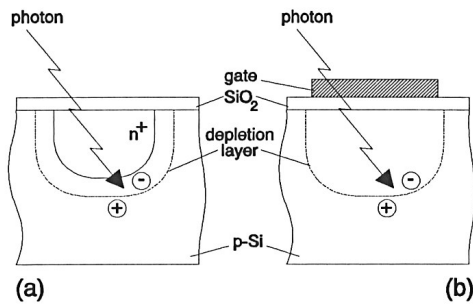
Electrons in the depletion region move to the oxide surface.

The addition of electrons is equivalent to filling the bucket.

Photo-conversion

Depletion regions in semiconductors collecting electrons and holes:
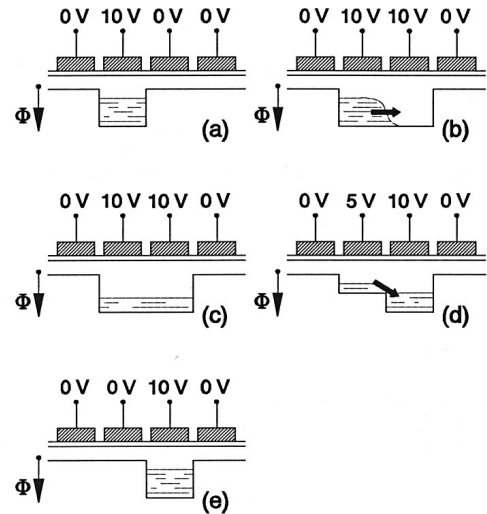

A diode has an inherent depletion region without applying a voltage. Can be used as a **photodiode**.

When a MOS capacitor is biased into depletion, it can collect charge generated by photons.
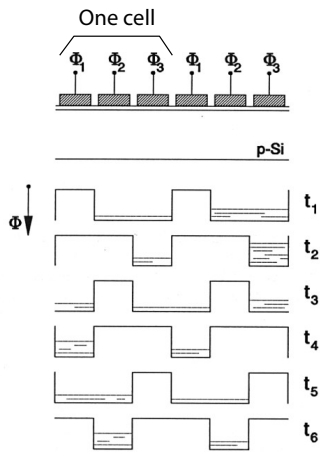
Charge transfer

By manipulating voltages of neighboring cells, we can move a bucket of charge one gate to the right.

Three-phase clocking system

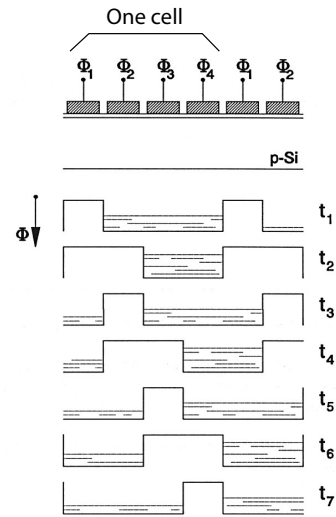With three gates, we can move disjoint charge packets along a linear array of CCD's.

One cell

Since all charge must be able to fit in one bucket, gate usage withing a cell is 33%.

Four-phase clocking system

Four gates requires more space than three, but the charge capacity is greater.
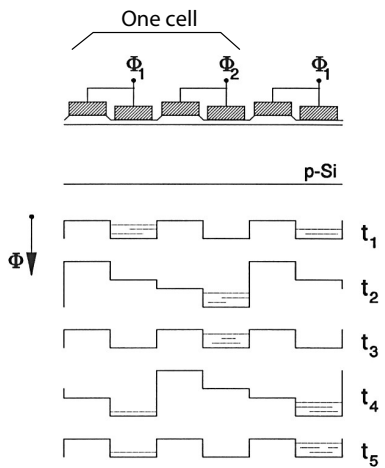
One cell

Here, all charge must fit into two buckets, giving a gate usage of 50%.
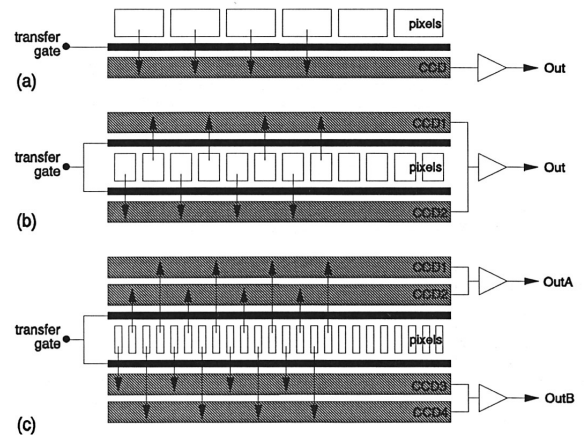
Two-phase clocking system

By varying gate structure, it is possible to use two gates per cell:

One cell

The efficiency is down to 25%, but by narrowing horizontal thickness of the blocking portion (left side) of each gate, it is possible to get ~40%.
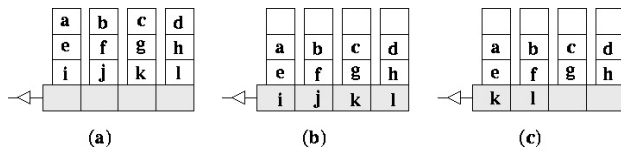
Linear array sensors

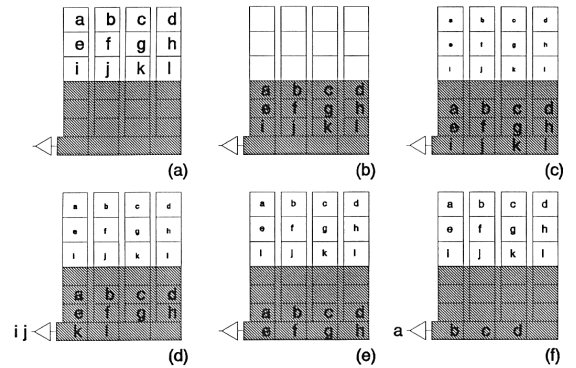(a) Linear imager

(b) Bilinear imager

(c) Qudralinear imager

Full frame CCD

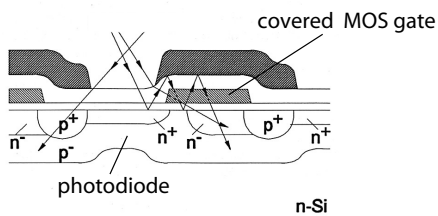(a) (b) (c)

Q: What shortcoming(s) does this design have?

Frame transfer (FT) CCD

(a) (b) (c)

(d) (e) (f)

Q: What shortcoming(s) does this design have?

Interline transfer (IT) CCD

(a) (b) (c)

(d) (e) (f)

covered MOS gate

p+   n+   n+   p+   n+

n−   p−

photodiode

n-Si
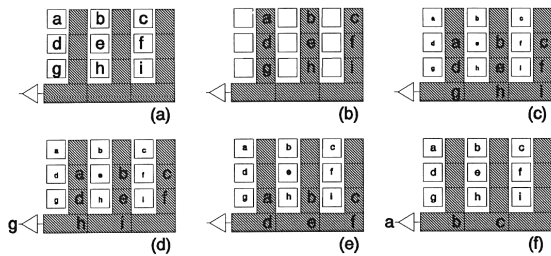
Q: What shortcoming(s) does this design have?

Frame interline transfer (FIT) CCD's

(a) (b) (c)

(d) (e) (f)
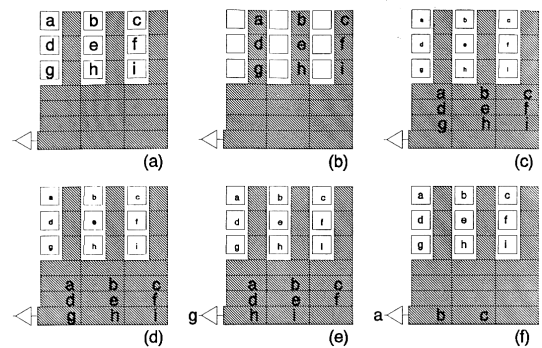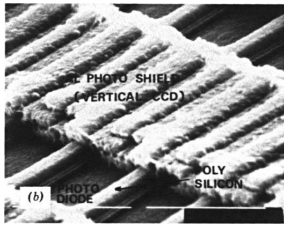
Q: What shortcoming(s) does this design have?
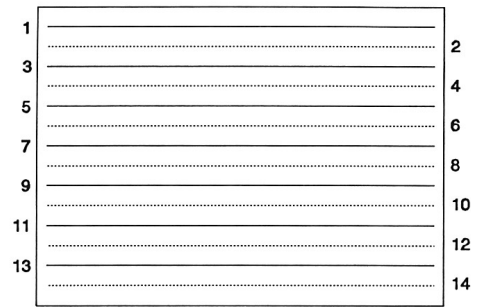
A closer look...
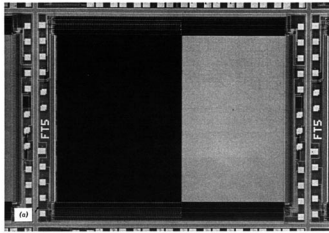
Frame transfer CCD
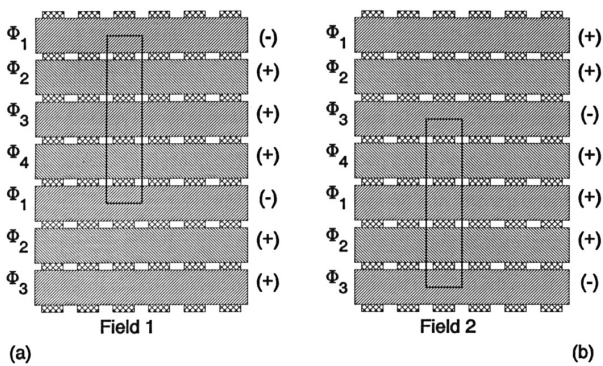

Interline transfer CCD
(SEM photograph)

Interlacing

Interlaced
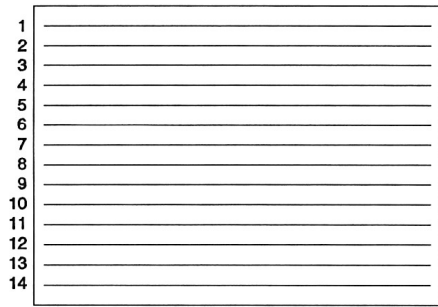
Progressive

Interlacing (cont'd)

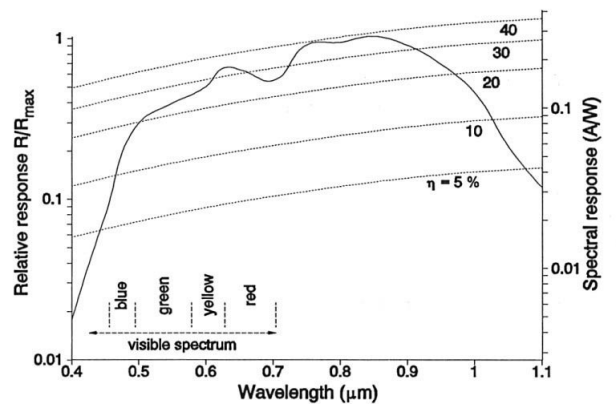Field 1 (a)   Field 2 (b)

By manipulating gate voltages, we can redefine cells.

In the FT CCD above, positive voltages define the charge collecting regions.

By shifting positive voltages, the cells shift vertically.
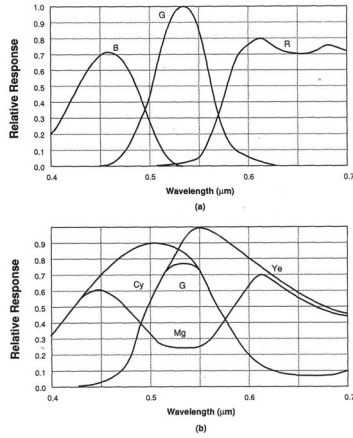
Spectral response

Typical spectral response of a linear MOS CCD imager:

Note the strong response in the infrared. An infrared filter ("hot mirror") is typically necessary.
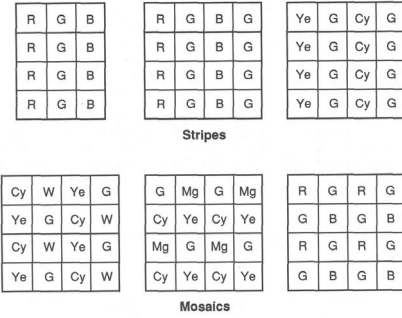
Color filters

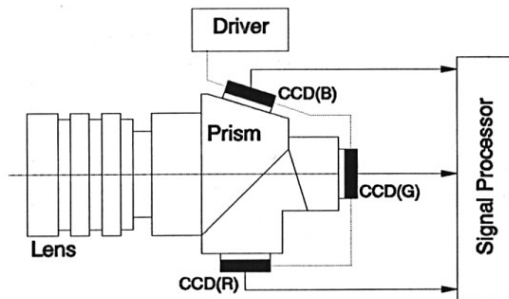Two capture color, different wavelength filters can be placed on the photodectors.

Single chip color filters

The filters can be distributed over a chip in several ways.

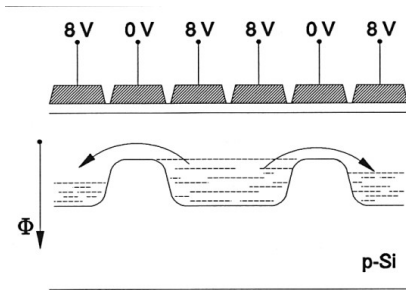**Q**: What is a shortcoming of a single chip color filter?

3-chip color cameras

Limitations of CCD's

Smear vs. aliasing

Blooming

Diffusion

Transfer efficiency

Noise

Dynamic range

Blooming

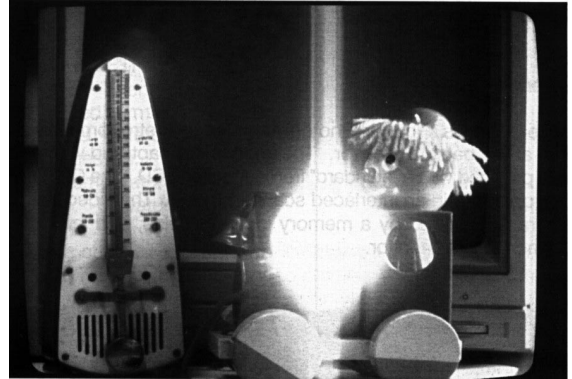8 V   0 V   8 V   8 V   0 V   8 V

Φ

p-Si

Blooming

Over-exposure causes charges to leak into neighboring cells.

Can be reduced with "anti-blooming" technology.

Example: smear and blooming

Diffusion

Si
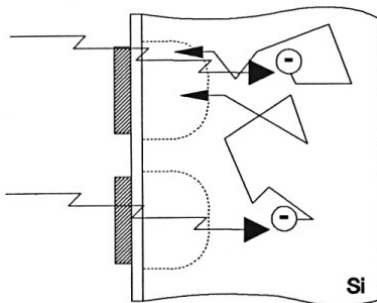
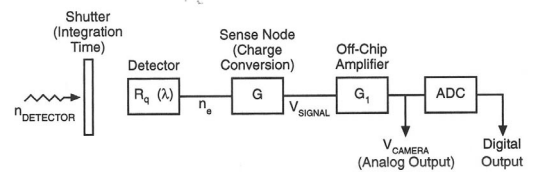Electrons generated outside the depletion region may wander into neighboring cells.

Noise

Here is a diagram of the CCD sensing process:

Shutter (Integration Time)

Detector

Sense Node (Charge Conversion)

Off-Chip Amplifier

$n_{DETECTOR}$ $R_q (\lambda)$ n_e G V_{SIGNAL} G_1 ADC

V_{CAMERA} (Analog Output)   Digital Output

Q: What kind of noise sources might you expect?

Dark current and photon shot noise

Electron-hole pairs are generated according to:

$$n_{photon} \sim t_{INT} I$$

where:

- I = irradiance of the light
- t_{INT} = integration time

They are also generated due to thermal agitation, yielding a "dark current":

$$n_{dark} \sim t_{INT} T^2 e^{-E_\Delta / kT}$$

where:

- T = temperature
- K = Boltzmann's constant
- E_Δ = energy constant that depends on materials

Dark current and photon shot noise

The electron generation process is a discrete counting process with unknown arrival times.

Such processes are described by Poisson statistics.

For a variable X obeying Poisson statistics:

$$\sigma^2 = \mu$$

Q: How should noise vary over an image?

Q: What happens to signal-to-noise (SNR) as signal increases?

Shot noise example

Original image

Variance (x32)

Bibliography

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Muller, R. and Kamins, T. Device Electronics for Integrated Circuits, 2nd Edition. John Wiley and Sons, New York, 1986.

Theuwissen, A. Solid-State Imaging with Charge-Coupled Devices. Kluwer Academic Publishers, Boston, 1995.